Effects from color entanglement in proton-proton and proton-nucleus collisions

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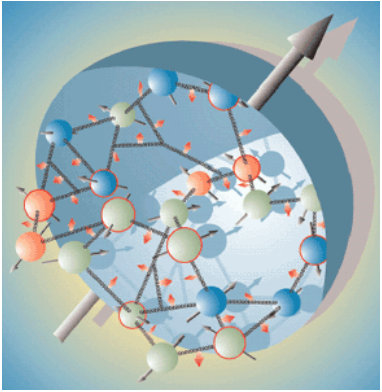
October 23, 2017

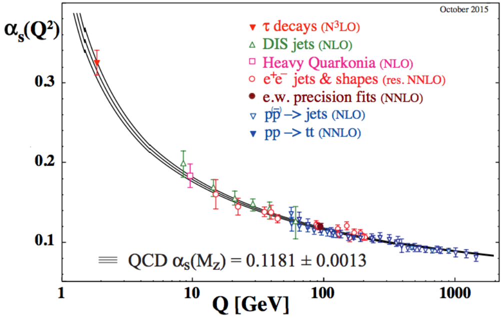
Quantum Chromodynamics

- QCD is *the* fundamental gauge theory describing the strong force
- Written in terms of quark and gluon (parton) degrees of freedom
- But we can only directly observe combinations of partons in the laboratory!
- Confinement and the non-Abelian nature of QCD: gluon self coupling and color charge



Probing Partons

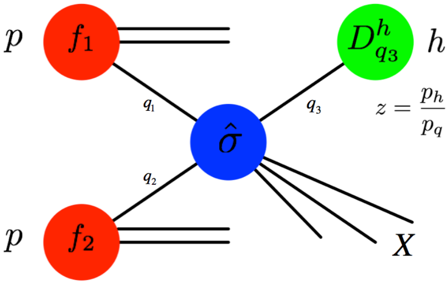
- Take advantage of running of the strong coupling constant - weak at large energies
- High energy interactions allow us to probe the partonic degrees of freedom
- Allows us to relate the gauge theory degrees of freedom to actual physical observables



PDG 2017

QCD Cross Sections

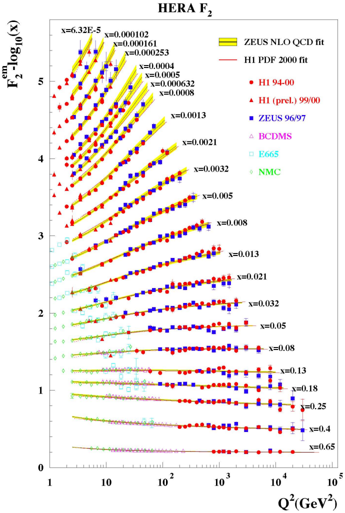
- To account for bound state nature of hadrons, cross sections are factorized
- Nonperturbative parton distribution and fragmentation functions (PDFs and FFs) are used to describe the individual partons within a hadron
- Functions are *nonperturbative*, must be constrained by data!
- Taken to be process independent and uncorrelated



$$\sigma = f_1(x, Q^2) \otimes f_2(x, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D^h_q(z, Q^2)$$

$$x = \frac{p_{parton}}{p_{proton}}$$

Mapping the Structure of the Proton



$$\sigma_{e^-+p\rightarrow e^-+h} \propto F_2(Q^2, x)$$

- Historically have used semi-inclusive deep-inelastic-scattering (SIDIS) and Drell-Yan (DY) as probes of hadron structure
  - SIDIS: $e^- + p \rightarrow e^- + h$
  - DY: $q + \bar{q} \rightarrow \ell^+ + \ell^-$
- Longitudinal structure of proton in terms of x mapped out over huge range of x and Q^2

Multidifferential QCD

- The last two decades have seen QCD push towards measurements of parton dynamics
- Phenomenological calculations now consider internal multidimensional structure
- Experimentalists have benefited from advanced facilities to observe multidimensional observables sensitive to parton dynamics
- What does the proton look like in terms of the quarks and gluons inside of it?
  - Position (2D)
  - Momentum (3D)
  - Flavor
  - Spin
  - Color (!)
- How can we use perturbative tools to learn about the nonperturbative aspects of QCD?

1D vs. 3D Nonperturbative Functions

- Historically nonperturbative functions are approximated as only dependent on the collinear momentum fraction x
- In reality there must be transverse structure due to the confined nature of the partons and the additional possibility of gluon radiation
- The unintegrated k_T distributions are explicitly dependent on transverse momentum

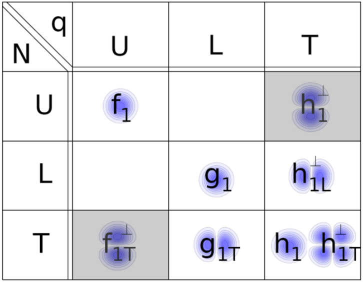
Parton Distribution Functions: $f(x) \rightarrow f(x, k_T)$

Fragmentation Functions: $D(z) \rightarrow D(z, j_T)$

- We can also add spin into the picture...

Transverse-Momentum-Dependent PDF Zoo

Transverse-Momentum-Dependent
(TMD) PDFs



N - Nucleon
q - Quark
U - Unpolarized
L - Longitudinally polarized
T - Transversely polarized

- 8 TMD PDFs describing transverse partonic structure, spin-spin, and spin-momentum *correlations!*

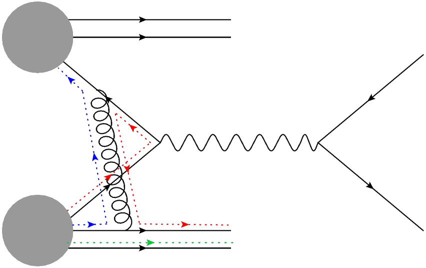
Image taken from Alexei Prokudin Spin 2016

Transverse-Momentum-Dependent Phenomenology

- In the collinear framework, nonperturbative functions are taken to be uncorrelated, universal, process independent functions
- In the transverse-momentum-dependent framework, it has been necessary to re-check these assumptions
- This has led to very interesting predictions...

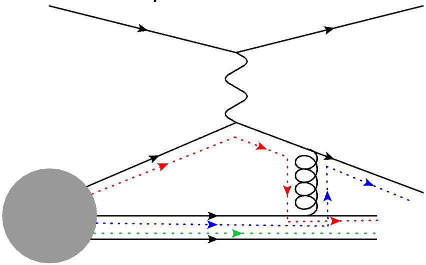
Universality in Transverse-Momentum-Dependent Functions

Drell-Yan: $q + \bar{q} \rightarrow \ell^+ + \ell^-$



Semi-Inclusive DIS:

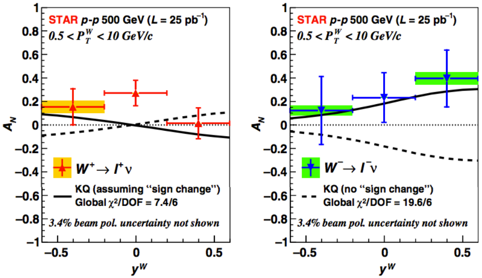
$e^- + p \rightarrow e^- + h$



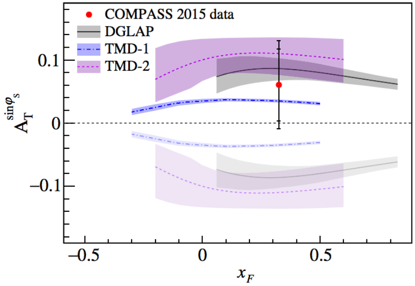
- Sign change in transverse-momentum-dependent PDFs with certain symmetry properties (PT odd) predicted due to initial-state vs. final-state gluon exchange with proton remnants between Drell-Yan and semi-inclusive DIS: process dependent PDF!
- Factorization of transverse-momentum-dependent PDFs and fragmentation functions still predicted to hold in these QED processes

First Measurement of Possible Modified Universality

- Semi-inclusive DIS Sivers asymmetries have been measured, e.g. by HERMES and COMPASS collaborations
- First measurements of Drell-Yan (type) processes just recently reported
- Data support prediction of process dependent transverse-momentum-dependent PDF (although still statistically limited)



PRL 116, 132301(2016)



PRL 119, 112002 (2017)

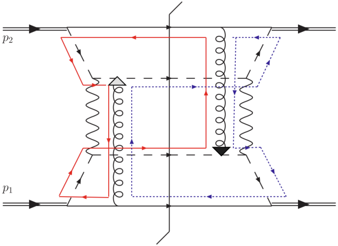
Factorization of Transverse-Momentum-Dependent Functions

- Factorization is still predicted to hold in semi-inclusive DIS and Drell-Yan and the previous example is a check of this

$$\sigma = f(x, k_T, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_q^h(z, j_T, Q^2)$$

- What about leading-order QCD processes where a colored quark or gluon is exchanged?
- Color present in both the initial and final state - therefore soft gluon exchange possible in both the initial and final state

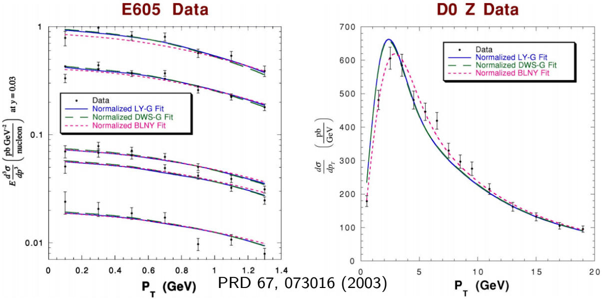
- Factorization breaking predicted in a transverse-momentum-dependent (TMD) framework for $p + p \to h_1 + h_2$ (PRD 81, 094006 (2010))
- TMD nonperturbative functions no longer defined - partons are quantum mechanically correlated via color across colliding hadrons!
- Consequence of soft gluon exchanges in both the initial and final state



- Predicted modified universality of certain TMD PDFs and factorization breaking from same physical process - color flow in action!
- Consequence of QCD as a non-Abelian gauge theory

Collins-Soper-Sterman (CSS) Evolution with Q^2

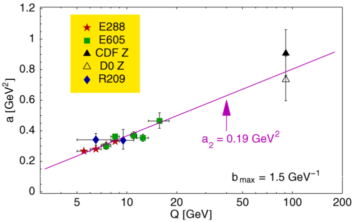
- CSS evolution first published in 1985. Similar to DGLAP evolution equation, but includes small transverse momentum scale
- Has been used to successfully describe global Drell-Yan and Tevatron Z^0 cross sections
- Clear qualitative prediction - momentum widths sensitive to nonperturbative transverse momentum increase with increasing hard scale
- Due to increased phase space for gluon radiation

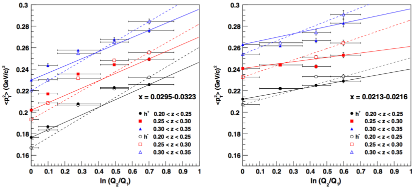


PRD 67, 073016 (2003)

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow theoretical prediction
- The evolution prediction comes directly out of the derivation for transverse-momentum-dependent (TMD) factorization
  - If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!

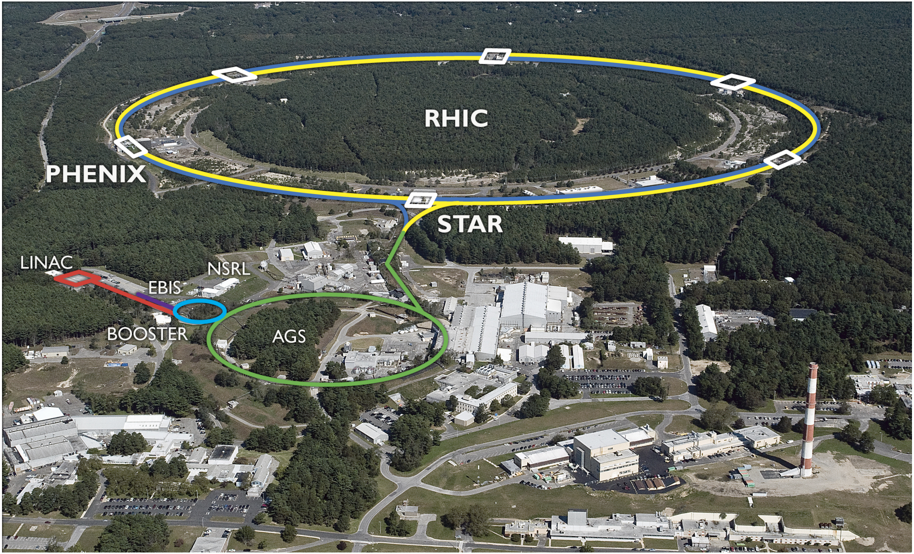
DY/Z - PLB 633, 710 (2006)





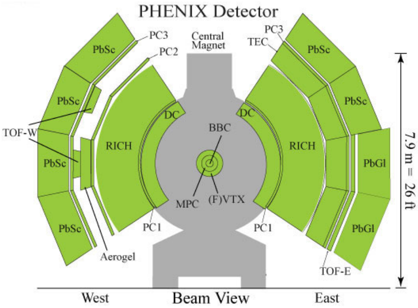
SIDIS - PRD 89, 094002 (2014)

Relativistic Heavy Ion Collider - RHIC at Brookhaven National Laboratory



PHENIX Detector

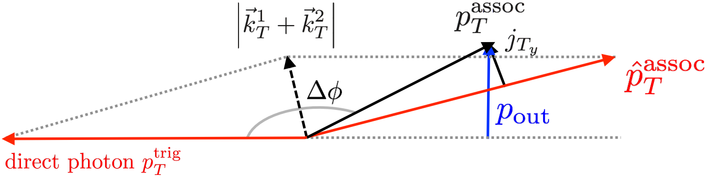
- PHENIX central arms
  - $\Delta\phi \sim \pi$
  - $|\eta| < 0.35$
- Electromagnetic Calorimeter (PbSc/PbGl) provides isolated direct photon and $\pi^0 \rightarrow \gamma\gamma$ detection
- Drift Chamber (DC) and Pad Chambers (PC) provide nonidentified charged hadron detection



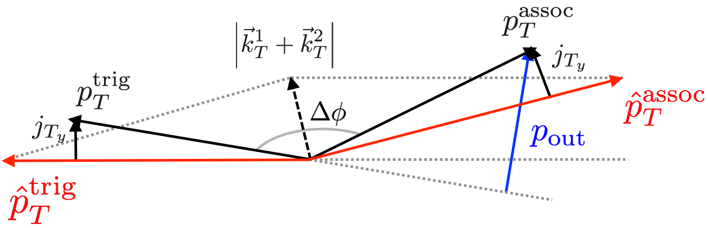
- Results from
  - $\sqrt{s} = 510$ GeV p+p
  - $\sqrt{s} = 200$ GeV p+p
  - $\sqrt{s} = 200$ GeV p+A

Angular Correlation Observables

Direct photon-hadron production

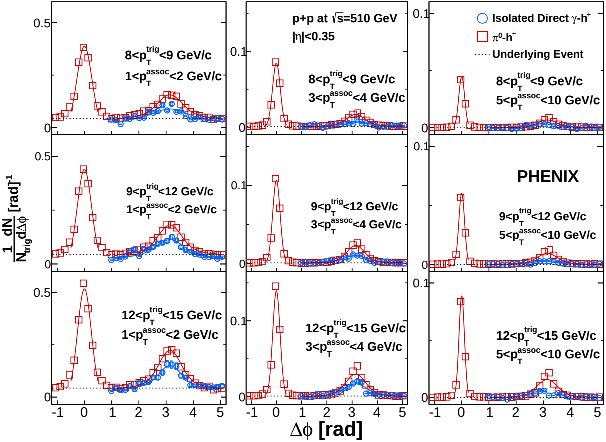


Dihadron production



$$p_{out} = p_T^{assoc} \sin \Delta\phi$$

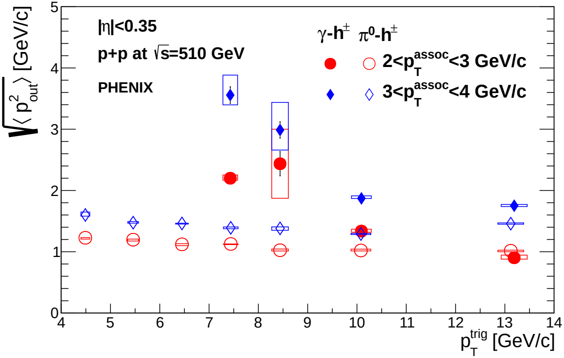
$\Delta\phi$ Correlations for π^0-h$^{\pm}$ and Direct γ-h$^{\pm}$

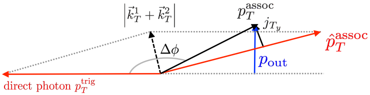


Phys. Rev. D 95, 072002 (2017)

- Two jet structure visible for π^0-h$^{\pm}$, isolation cut at $\Delta\phi \sim 0$ for direct γ-h$^{\pm}$
- Direct γ-h$^{\pm}$ probes smaller jet energy due to emerging from hard scattering at LO

$\sqrt{\langle p_{out}^2 \rangle}$ Extracted from Fits to $\Delta\phi$ Correlations



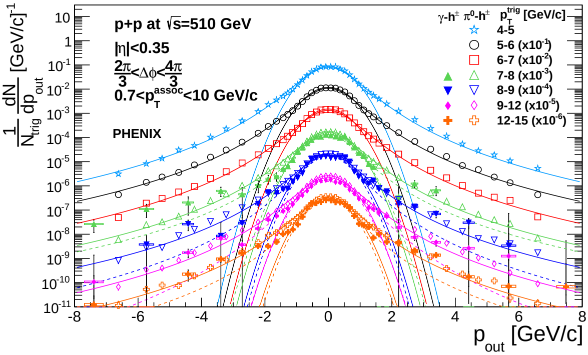


Phys. Rev. D 95, 072002 (2017)

- $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width in momentum space
- Decreases with hard scattering scale p_T^{trig}, opposite of semi-inclusive DIS and Drell-Yan!
- Sensitive to perturbative *and* nonperturbative k_T and j_T; fits are to entire away-side jet

p_{out} Distributions

- p_{out} shows two distinct regions: Gaussian and power law
- Gaussian fits clearly fail past $\sim$1.3 GeV/c
- Indicates transition from nonperturbative to perturbative k_T and j_T

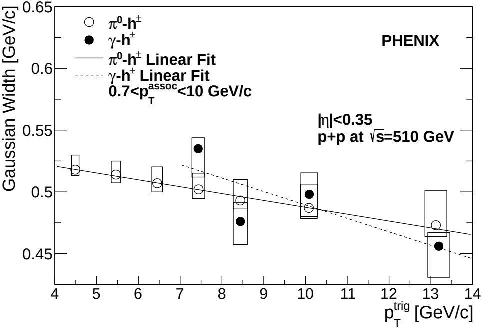


Phys. Rev. D 95, 072002 (2017)

- Note: Curves are Kaplan and Gaussian fits, not calculations!!

Gaussian Widths of p_{out}

- Gaussian widths of p_{out} vs. p_T^{trig} are sensitive to *only* nonperturbative k_T and j_T
- Widths decrease with hard scale, opposite of semi-inclusive DIS and Drell-Yan!

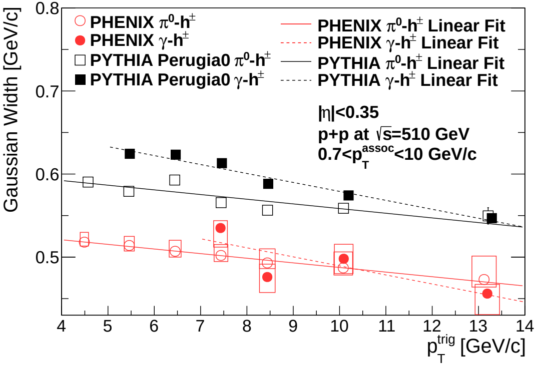


Phys. Rev. D 95, 072002 (2017)

PYTHIA Event Simulation

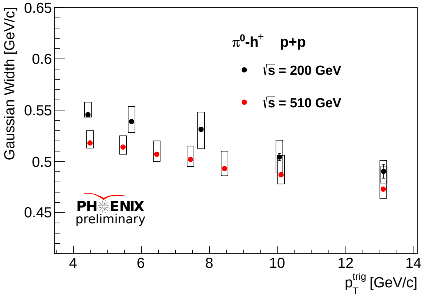
- PYTHIA full event $p+p$ simulation replicates the negative slope of the Gaussian widths
- Magnitudes of widths from PYTHIA show $\sim$15% difference from data despite slope being replicated
- Very surprising - PYTHIA doesn't explicitly include transverse-momentum-dependent functions

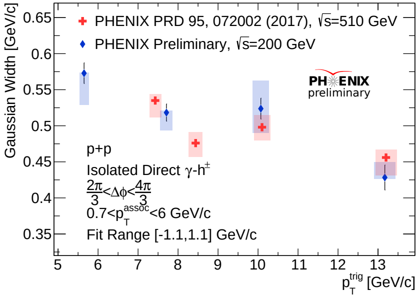
Phys. Rev. D 95, 072002 (2017)



- BUT it does allow initial and final state gluon exchanges, which are the necessary physical mechanisms for factorization breaking

New $\sqrt{s} = 200$ GeV $p+p$ Results



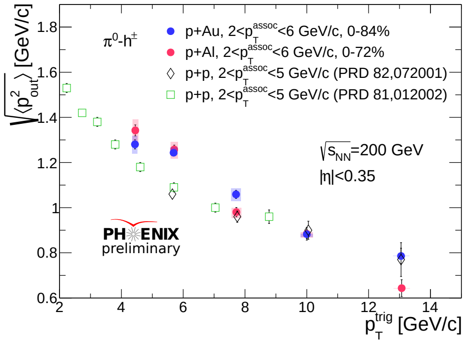


- New $\sqrt{s} = 200$ GeV results allow the nonperturbative momentum widths to be studied as a function of $\sqrt{s}$
- Could provide information on possible correlations between x and k_T that leads to the decreasing widths

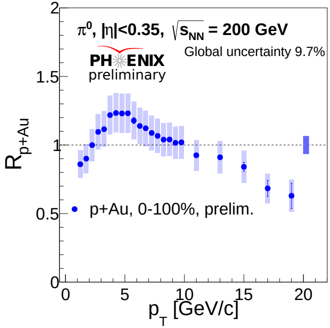
Nuclear Effects

- In 2015 RHIC collided, for the first time ever, p+Al and p+Au at $\sqrt{s}$ =200 GeV
- Unique opportunities abound to study correlations as a function of:
  - Number of hadrons in collisions - do stronger color fields lead to modified effects?
  - Nuclear size - Modification from $p+p \rightarrow p+\mathrm{Al} \rightarrow p+\mathrm{Au}$?
  - Centrality/multiplicity - Do the number of final-state particles affect factorization breaking effects?

$\sqrt{\langle p_{out}^2 \rangle}$ in p+Au and p+Al



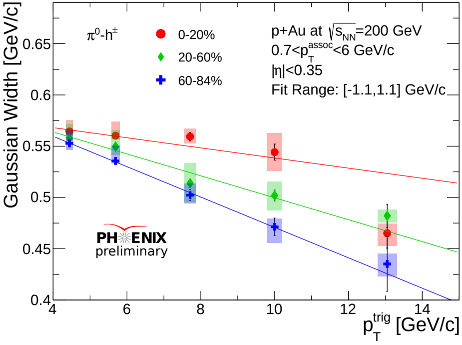
$$R_{pA} = \frac{(d^2N/dp_T d\eta)_{pA}}{\langle N_{binary} \rangle (d^2N/dp_T d\eta)_{pp}}$$



- Reminder: $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet-width in momentum space
- See larger $\sqrt{\langle p_{out}^2 \rangle}$ in p+A compared to published p+p data
- Relation to Cronin effect (enhancement at ∼5 GeV)?? Correlations could provide additional information
- Note: $4 < p_T^{trig} < 8 \otimes 2 < p_T^{assoc} < 6$ within R_{pA} enhancement region

Gaussian Widths of p_{out}

- Dihadron correlations in p+Au show clear centrality (final-state multiplicity) dependence
- Nonperturbative away-side jet widths larger in more central events
- Effects from k_T broadening? Multiple scattering? Multiple partonic interactions?



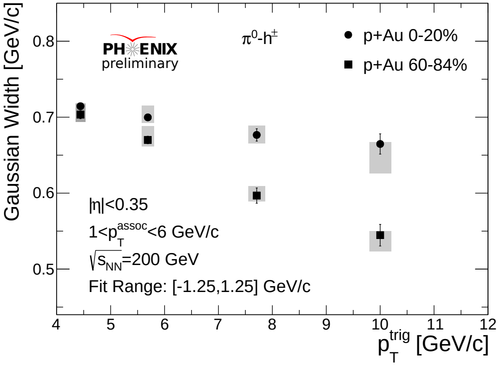
0-20% Centrality

20-60% Centrality

60-84% Centrality

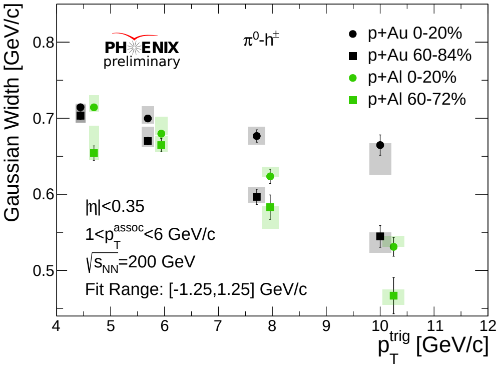
Cold Nuclear Matter Effects: Centrality Dependence on Nucleus Size

- Centrality dependence in p+Au clearly seen
- Is there a similar dependence in p+Al?



Cold Nuclear Matter Effects: Centrality Dependence on Nucleus Size

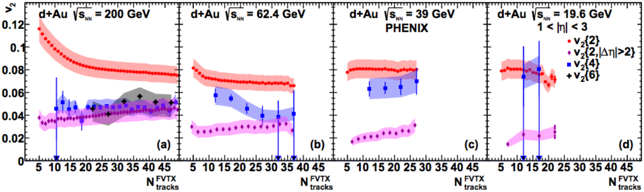
- Centrality dependence in p+Al as well, although not as strong as in p+Au
- Central and peripheral p+Al do not show as big a difference as central and peripheral in p+Au
- Central p+Al similar to peripheral p+Au - multiplicity dependence



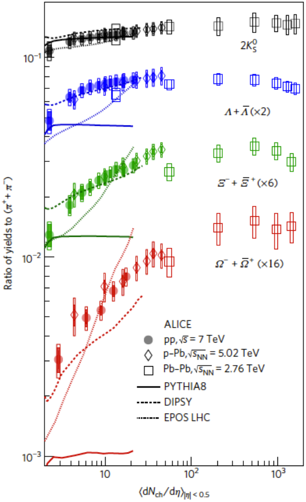
p+Al points shifted for visibility

Relation to High Multiplicity?

- Surprising results from RHIC and LHC show novel phenomena in high multiplicity p+p and p+A
- What role does color play in these measurements?
- p+A measurements sensitive to color entanglement also probing multiple partonic interaction effects

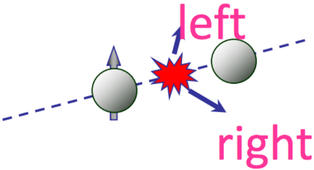


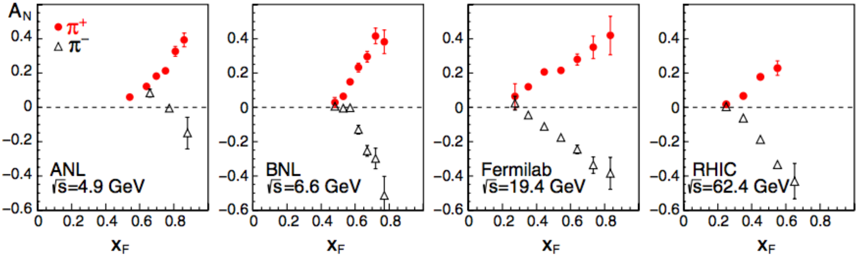
arXiv:1707.06108



Nature Phys. 13 (2017) 535-539

- Transverse single spin asymmetries show up to 40% left-right asymmetry in $p+p$ collisions
- Only $\sim$5% in semi-inclusive DIS
- Effects from color contributing?

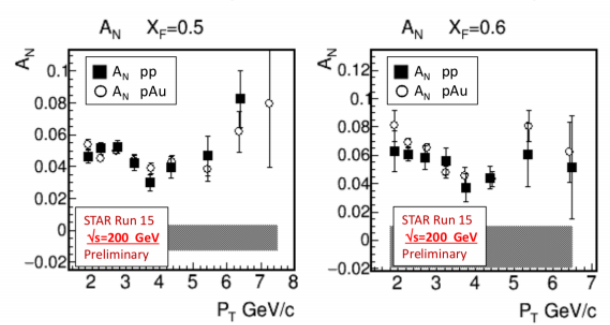




Rev. Mod. Phys. 85, 655 (2013)

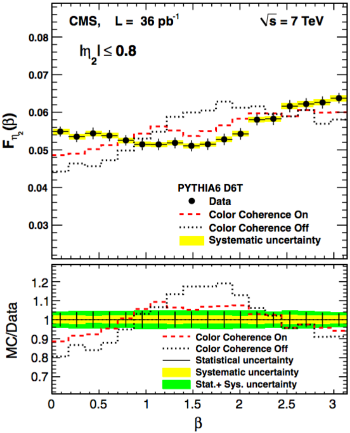
Relation to Huge Transverse Single Spin Asymmetries?

- Correlations sensitive to color entanglement do not follow perturbative evolution
- Transverse single spin asymmetries are perturbatively predicted to go to 0 with increasing p_T
- Nonzero ($\sim$7%) asymmetries have been measured up to $p_T \sim 7$ GeV
- Transverse single spin asymmetries seem to not follow perturbative evolution as well



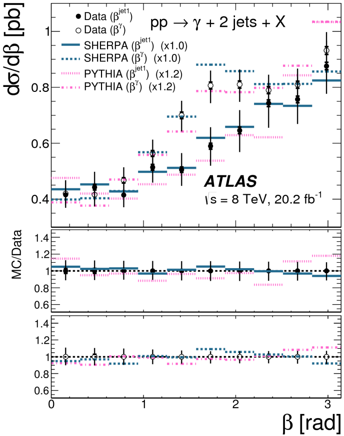
Relation to LHC Color Coherence Measurements

CMS Dijet+jet



Eur. Phys. J. C74 (2014) no.6,2901

ATLAS γ-jet+jet

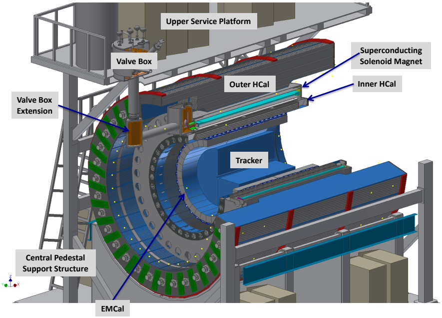


Nucl. Phys. B 918 (2017) 257-316

- ATLAS/CMS find that additional radiated jet is more likely to be found towards opposite rapidity

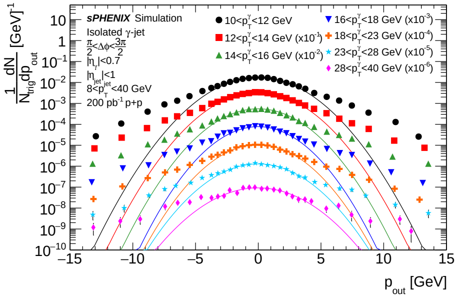
Future Color Entanglement Measurements

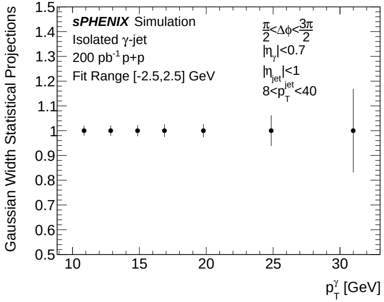
- Color interactions can only be probed in hadronic interactions
- We must measure them before the future Electron Ion Collider is constructed
- New RHIC experiment sPHENIX will be a dedicated jet detector sensitive to nonperturbative parton dynamics



Estimated γ-jet Statistical Precision

- γ−jet is the ideal channel - limits color flow possibilities with sensitivity to only k_T
- RHIC kinematics important - need high p_T processes which still have sensitivity to the nonperturbative physics
- sPHENIX will have excellent statistical precision for γ-jet at RHIC *for the first time*
- Will extend PRD 95, 072002 (2017) to study x dependence as well as role of fragmentation with tracking capabilities





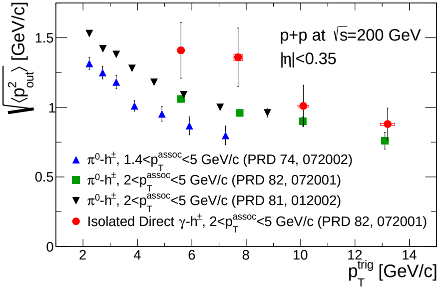
Conclusions

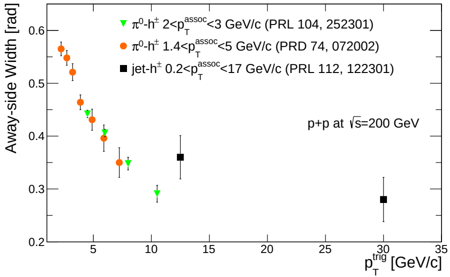
- Theory and measurements are now probing parton dynamics - QCD color in action!
- Nonperturbative momentum widths from PHENIX $p+p$ and $p+$A show opposite behavior from Collins-Soper-Sterman hard scale evolution, which comes from transverse-momentum-dependent factorization theorem
- $p+$A correlations show multiplicity dependence - potential relations to multiple scattering effects and multiple partonic interaction physics now being probed at both RHIC and the LHC
- sPHENIX will be ideal facility to study nonperturbative photon-jet effects in $p+p$ and $p+$A collisions
- Synthesizing information from many different collision systems is joining historically separate fields - it's all QCD!

Back Up

$\sqrt{s}$=200 GeV Results from RHIC

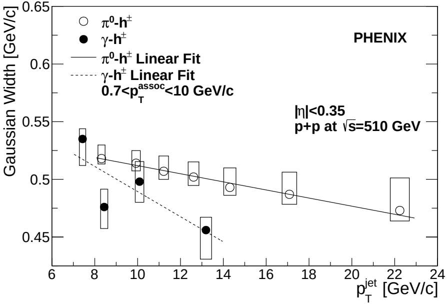
- Previous PHENIX result at $\sqrt{s}$=200 GeV to lower p_T^{trig} (PRD 81, 012002 (2010))
- Shows $\sqrt{\langle p_{out}^2 \rangle}$ over lower range of p_T^{trig}
- Also can plot away-side width in angular space - same trend over large range of p_T^{trig}



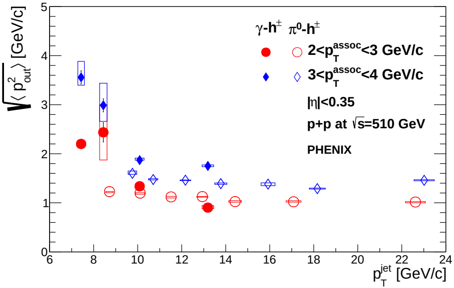


$\langle z_T \rangle$ with Gaussian Widths

- $\langle z_T \rangle$ p_T^{trig} correction was also applied to Gaussian widths vs. p_T^{trig}
- $\langle z_T \rangle$ more or less amounts to a scale factor of 2 difference in the slope



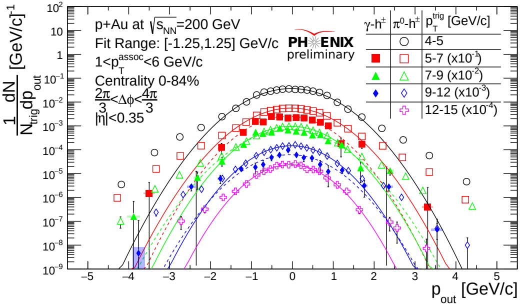
$\sqrt{\langle p_{out}^2 \rangle}$ vs. p_T^{jet}

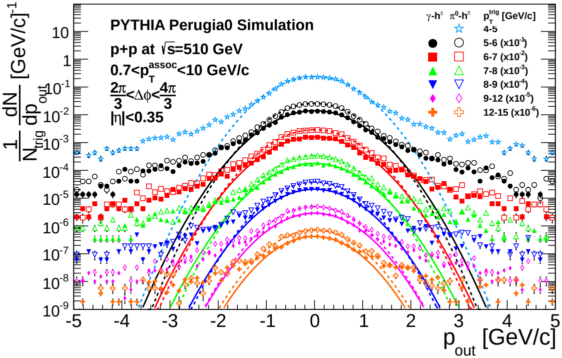


- Examined $\sqrt{\langle p_{out}^2 \rangle}$ as a function of p_T^{jet} as well
- $p_T^{jet} = p_T^{trig}$ for direct photons
- $p_T^{jet} = p_T^{trig}/\langle z_T \rangle$ for π^0s, with $\langle z_T \rangle$ estimated using PYTHIA
  - $\langle z_T \rangle = \frac{p_T^{trig}}{\hat{p}_T^{trig}}$
- The $\sqrt{\langle p_{out}^2 \rangle}$ distributions almost form a continuous function?

p+Au p_{out} Distributions

- p+Au p_{out} distributions in both $\pi^0 - h^\pm$ and $\gamma - h^\pm$ show similar shapes to p+p
- Gaussian core transitions to power-law shape at large p_{out}
- Limited statistical precision in $\gamma - h^\pm$ channel, but any centrality dependence could be observed in $\pi^0 - h^\pm$

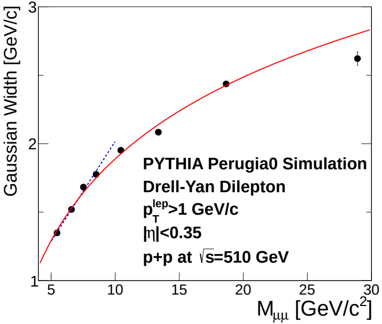


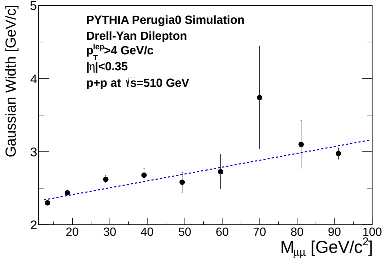


- Can construct p_{out} distributions for direct photons and dihadrons in PYTHIA as well for direct comparison
- PYTHIA replicates the nonperturbative to perturbative transition in the p_{out} distributions

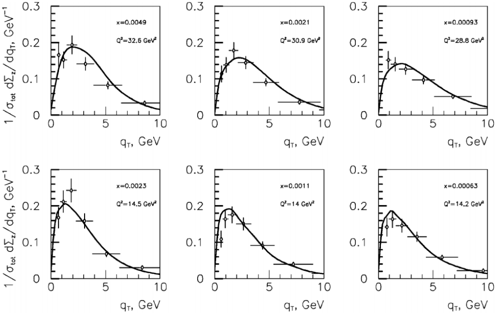
PYTHIA $p+p$ Event Simulation

- To make a comparison, used PYTHIA event generator simulation
- PYTHIA reproduces expectation from CSS evolution in Drell-Yan over large range of $M_{\mu\mu}$

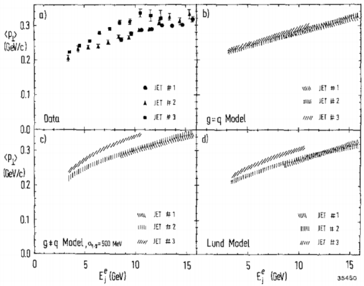


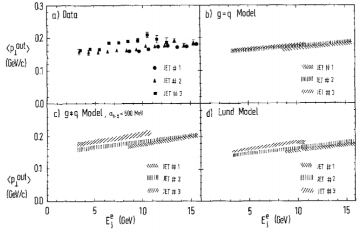


SIDIS and e^+e^- Annihilation Momentum Widths



PRD 61, 014003





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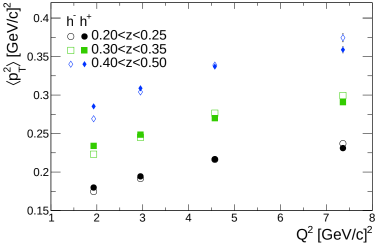
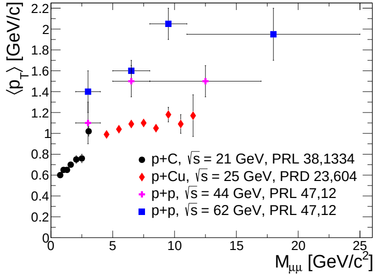
DY/Z and SIDIS in CSS Evolution

SIDIS - Eur. Phys. J. C(2013) 73,2531

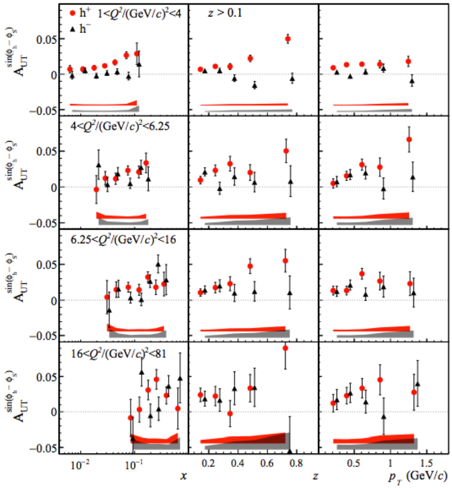




FNAL fixed target DY

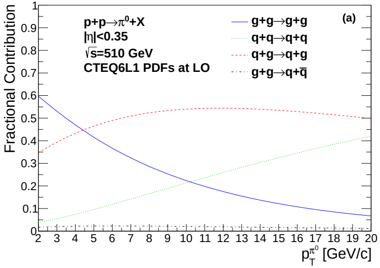
- Measurements show that DY and SIDIS follow prediction of CSS evolution
- The CSS evolution equation comes directly out of the derivation for TMD factorization

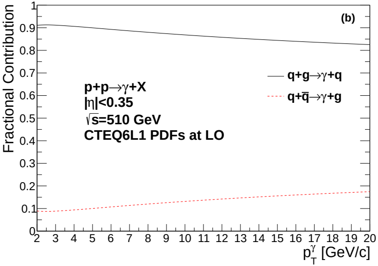
- SIDIS Sivers measurement shows ∼5% asymmetries
- Smaller than the asymmetries measured in hadronic collisions
- SIDIS only sensitive to final-state effects from gluon exchanges



Phys. Lett. B770 (2017) 138-145

Partonic Contributions to Processes at LO



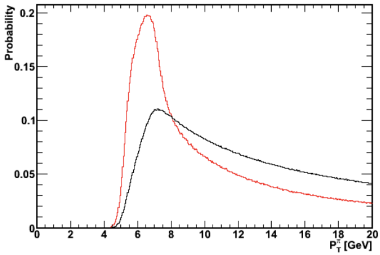


- π^0 contribution changes from gluon dominated at low p_T to mix of quark and gluons at high p_T
- Direct photon contribution dominated by QCD Compton scattering at all p_T
- NLO corrections small at midrapidity (Phys. Lett. B 140,87)

Analysis Methods

- Correlated π^0−$h^\pm$ or isolated γ−$h^\pm$ are collected and corrected with:
    - Charged hadron efficiency
    - Acceptance correction
- Direct photons undergo additional statistical subtraction to remove decay photon background, estimated with Monte Carlo probability functions
- Isolation and tagging cuts remove decay photon background and NLO fragmentation photons

Probability for a π^0 to decay to a photon which could not be tagged with $5 < p_T < 7$ GeV/c in PHENIX

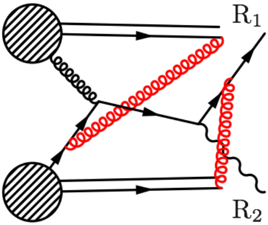


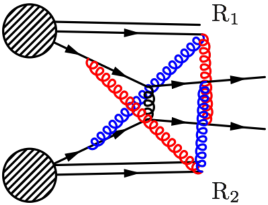
$$Y_{dir}^{iso} = \frac{1}{R_\gamma^{iso} - 1}\left(R_\gamma^{iso} Y_{inc}^{iso} - Y_{dec}^{iso}\right)$$

PRD 82,072001 (2010)
PRC 80,024908 (2009)

Direct Photons and Dihadrons

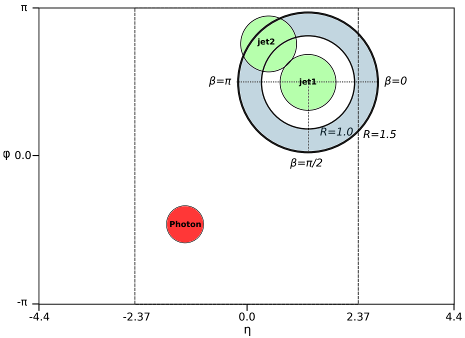
- Direct photon-hadron and dihadron correlations both predicted to be sensitive to factorization breaking effects in PHENIX
- Assuming factorization, direct photon-hadrons probe three nonperturbative functions, while dihadrons probe four
- Direct photons offer one less avenue for gluon exchange in the final-state: fewer/different effects?



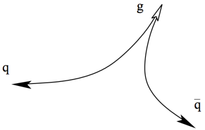


Relation to LHC Color Coherence Measurements

- CMS/ATLAS measure dijet+jet or photon-jet+jet with angular variable β
- β is the angle in ϕ, η space between the away-side jet and third additional radiated jet
- $\beta \sim$0 corresponds to jet towards similar rapidity
- $\beta \sim \pi$ corresponds to jet towards opposite beam rapidity



More about Color Coherence



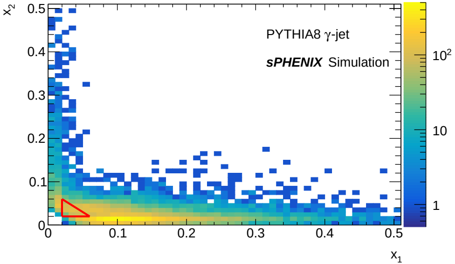
- Radiation "drags" color away from vertex
- Destructive interference occurs away from emitted gluons
- Soft radiation inhibited in certain areas
- Leads to certain regions of phase space where gluons constructively or destructively interfere

- See the following references
  - Phys. Rev. D 50,5562 (1994)
  - Phys. Lett. B 414 (1997) 419-427
  - Dokshitzer, Yuri. *Basics of Perturbative QCD* (Editions Frontieres, 1991) Chapters 4,5,9

Extending PHENIX Kinematic Reach

- Central-forward (top) and central-central (bottom) γ-jet x_1,x_2 reach at $\sqrt{s} =$ 510 GeV. Red triangle indicates x_1-x_2 reach of PHENIX PRD 95, 072002

Central-Forward γ-jet



Central-Central γ-jet